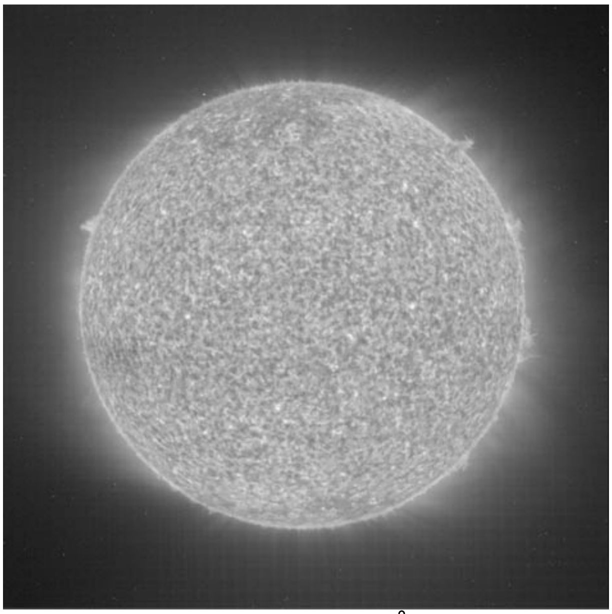
Solar Transition Region

The solar transition region can generally be defined as those plasmas at temperatures between 2×10^4 and 1×10^6 K, a temperature regime bridging the CHROMOSPHERE and CORONA. Prior to the space age, the transition region was unobserved although the existence of the higher-temperature corona was known. Spectral lines formed at transition region temperatures are found primarily below 2000 Å where they are strongly absorbed by the Earth's atmosphere. It was termed the transition region since it was thought to be a thin region of the atmosphere where an abrupt transition from a relatively cool, dense plasma to a hot, highly ionized, tenuous extended plasma occurred. Understanding the solar transition region is an important piece of the great puzzle of determining how the outer solar atmosphere is heated. More recently, interest in the transition region has increased as it is recognized that these plasmas are highly dynamic, displaying such events as jets, explosive events and high-speed flows.

Spectroscopy of the transition region

Observation of the solar transition region requires the use of spectroscopic techniques to isolate spectral lines formed at transition region temperatures. For example, helium has three ionic species: He I, neutral helium, He II, singly ionized helium, and He III, completely ionized helium. In the solar transition region, all three species are present but He II is the dominant species. The ionization state, the relative fractions of the three species, is determined by a balance between the competing processes of ionization and recombination of free electrons with the ions. At 6×10^4 K, He II is the most populous helium ion since at that temperature the free electrons have sufficient energy to ionize neutral helium (He I) but not enough energy to strip away the remaining bound electron to transform He II into completely ionized He III. The emission of He II spectral lines is produced by the collisional excitation of the bound electron to excited levels which then spontaneously decay to lower levels. The Lyman α line (the 1s–2p transition) of He II at 304 Å is a very strong line. It is much stronger than other lines at nearby wavelengths so that it can be fairly easily isolated and observed. Images of the Sun in the light of He II $\lambda 304$ are shown in figures 1 and 2. These images were obtained with the Extreme-Ultraviolet Imaging Telescope (EIT) instrument on the Solar and Heliospheric Observatory (SOHO) which uses narrow-bandpass coatings on the telescope mirrors to isolate strong spectral lines. Figure 1 was obtained near the minimum of the solar activity cycle and figure 2 was obtained when the Sun was more active.



EIT He II 304Å

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Figure 1. The solar transition region near the minimum of the solar activity cycle seen in He II $\lambda 304$.

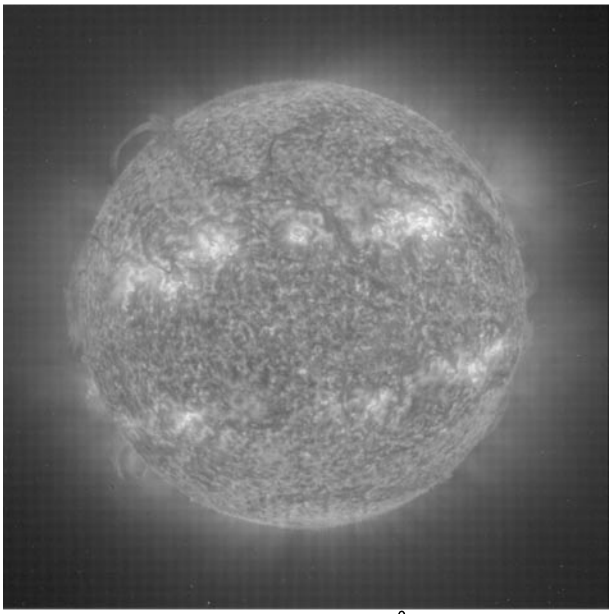

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Figure 2. The solar transition region as the Sun approached the maximum of the solar activity cycle seen in He II $\lambda 304$.

Temperatures, Densities, Emission Measures, Elemental Abundances

Essentially all of our information about the solar transition region comes from the analysis of spectral lines. Figures 1 and 2 show that much can be learned from images of the intensity of spectral lines. More detailed observations of the transition region are made with spectrographs which can disperse the solar spectrum in order to pick out spectral lines of particular interest.

The most direct piece of information that can be obtained about a spectral line is its intensity. The intensity of a line depends on how efficiently the line is produced and how many of the ions that produce the line are in the observed plasma. In the transition region and corona, most lines are produced by collisional excitation of the ion by free electrons. The emission rate is the product of two factors, the electron flux (the electron density multiplied by the electron velocity) and the collision cross section. The cross section is typically large for allowed or resonance transitions and small for forbidden transitions. The number of ions producing the line in the observed plasma is given by the products of the relative population of that ion with respect to all other ions of that element, the density of that element with respect to hydrogen (the elemental abundance) and the density of hydrogen (essentially equal to the electron density) in the observed plasma. Consequently, if we know the temperature, from the calculated ionization balance, the elemental abundance (from other measurements) and the collision cross section, from calculations, we can derive the emission measure ($\int N_e^2\,\mathrm{d}V$) at a given temperature directly from the line intensity. The emission measure provides considerable information about the temperature and density structure of the solar plasma.

A variety of techniques for determining the temperatures and densities of transition region and coronal plasmas are discussed in the article SOLAR SPECTROSCOPY AND DIAGNOSTICS.

Velocity measurements

The spectroscopy of the solar transition region can be taken one further step further to look at spectral line profiles. The object of this is to use the DOPPLER EFFECT to provide information about the velocities in the regions producing the spectral line. If a plasma is moving along the line of sight to the observer, the spectrum of the emitting plasma is shifted in wavelength by the amount $\Delta\lambda = (v/c)\lambda$ where v is the velocity of the observed plasma along the line of sight, and c is the speed of light (in the same units as v) and λ is the rest wavelength of the spectral line (in the same units as $\Delta\lambda$). Plasmas moving toward the observer are shifted to shorter wavelength (blueshift) and plasmas moving away from the observer are shifted to longer wavelength (redshift). If these shifts are observed near disk center, a blue shift corresponds to an outflow and a redshift corresponds to a downflow. At the limb, these shifts indicate horizontal flows.

Figure 3 shows profiles of C IV λ1548 and λ1550 in an active region and sunspot. The profiles are dispersed in wavelength from left to right and position in the quiet Sun runs from top to bottom. Large redshifts can be seen in the sunspot and indicate downflow velocities of 100–150 km s^{-1}. Above the sunspot spectra, one can also see a very small region with exceptionally wide line profiles. These are signatures of explosive events which will be discussed later. These spectra were obtained with the High

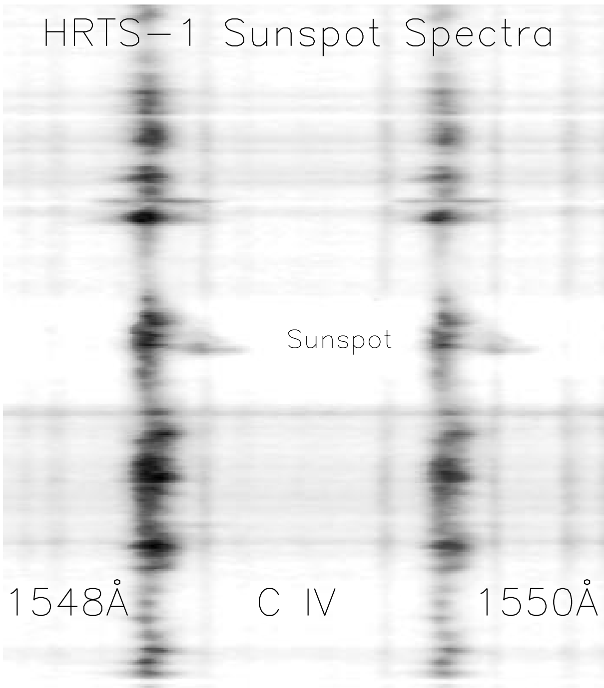


Figure 3. HRTS spectral line profiles of C IV, formed at 1×10^5 K, in an active region and sunspot.

Resolution Telescope and Spectrograph (HRTS) during a rocket flight.

Spectral observations often show that the line has a width that is wider than the spectral resolution of the spectrometer. Part of this excess line width is caused by the motions of the ions which follow a Maxwellian velocity distribution specified by the temperature of the plasma. On examination, one finds that transition region profiles are even broader than would be predicted from the temperature of the ion that emits the line. This excess broadening is called the nonthermal width of the line and is apparently due to motions in the plasmas on spatial scales below the spatial resolution of ultraviolet spectrographs currently in operation. The thermal and nonthermal broadening results in line profiles that have a shape that is nearly Gaussian. Also evident is the net Doppler shift of spectral line profiles of the order of 10 km s^{-1} caused by plasma flows in spicules, loops or other structures. Even more interesting are the occasional line profiles that are non-Gaussian and highly Doppler shifted. These are found in more spectacular events such as jets, ejecta and explosive events.

Elemental abundance variations

For many years, it has been assumed that the relative abundance of elements in solar plasmas does not vary. For example, the standard abundance of iron is about 4×10^{-5} that of hydrogen. The abundances are the result of nuclear processes that ended many years ago. For every parcel of solar plasma, this ratio is now expected to be the same. Once the variability of relative elemental abundances was considered a possibility, it was found that relative abundances in the corona were not the same as in the photosphere, that abundances seemed to change during flares and structures with nonstandard abundances were found fairly commonly. The key ingredient in the elemental abundance variations is the first ionization potential (FIP) of the element, or, the energy needed to ionize the neutral species of the element. Elements with low FIP values, such as Mg, Ca, Si and Fe, are enhanced in coronal plasmas relative to photospheric plasmas. The fact that the effect is correlated with the FIP indicates that the separation occurs at fairly low temperatures.

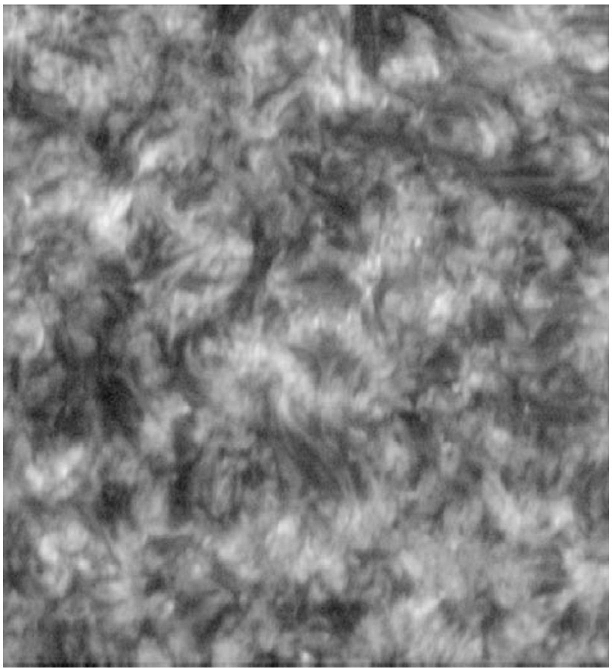
A more detailed discussion of this topic is given in SOLAR TRANSITION REGION.

Structure

Large-scale structure of the transition region

Lines formed at transition region temperatures are emitted in most of the large-scale structures that appear on the Sun: the quiet Sun, coronal holes, active regions, prominences, sunspots and solar flares. All of these structures are a result of the interplay between magnetic fields and plasmas.

In the quiet Sun, the magnetic fields are dominated by fields associated with the supergranulation. Here, the supergranular motions in the photosphere sweep the magnetic flux elements from the supergranular cell centers to the cell boundaries. The new magnetic flux that emerges in the cell centers appear to include both positive and negative polarities (upward- and downward-pointed magnetic fields), as if they were the emergence of small kinks in a magnetic flux rope. Consequently, the magnetic fields at the cell boundaries are also bipolar. As a result of the continuous reconnection of magnetic fields, the net result is a complex web of magnetic field lines connecting opposite magnetic field polarities. This magnetic field structure is reflected in the patterns of transition region line emissions. At relatively low temperatures, mostly the base of these short loops is outlined. The corresponding structures in the chromosphere are spicules. At 10^5 K, for example in C IV lines, structures that are the extensions of the cooler chromospheric models are typical. At higher transition region temperature, longer and more complete loops become apparent. A high-resolution image of the quiet transition region obtained with the SUMER instrument on SOHO is shown in figure 4.



SUMER Image of the Quiet Sun in O VI

Figure 4. The quiet transition region seen in O VI, formed at 3×10^5 K, obtained with the SUMER instrument on SOHO.

The magnetic field in coronal holes is predominantly of one polarity so that the large-scale field extends outward from the Sun and participates in the high-speed solar wind streams. The unipolar nature of coronal hole fields is the result of remnants of active region fields that are swept to the poles during the declining phase of the solar cycle. Nevertheless, the fields in the coronal hole are still pushed around by a supergranular flow pattern that arranges the fields into a supergranular pattern similar to that found in the quiet Sun, except that the fields are mostly of a single polarity. Bipolar fields continue to emerge in the cell centers but, since these have no net polarity, the polarity of the coronal hole fields is unchanged. In transition region lines, the intensity pattern is still that of the supergranular network although it is somewhat less intense than in the quiet Sun. A characteristic structure of the transition region in coronal holes is the macrospicule. These are similar to chromospheric spicules but are about 10 times larger. They typically jet out above the limb and either fade in place or fall back towards the photosphere. Macrospicules can be seen at the top and bottom of the solar images shown in figure 1.

SOLAR ACTIVE REGIONS, consisting of sunspots and plage regions, contain the most concentrated large-scale magnetic fields. The strongest fields are in the sunspots but these have no clear signature in transition region lines. Sunspots on average are neither particularly bright nor dark and cannot be located simply from an image of the transition region. Active region plages are often simply regions of relatively bright emission, particularly at low transition region temperatures. For increasing temperatures, the bases of coronal loops and extended portions of loops are outlined. As temperatures approach 1×10^6 K, the loops become more complete as is seen in coronal lines.

SOLAR PROMINENCES are relatively cool plasmas that are typically situated along magnetic 'neutral' lines where the dominant photospheric magnetic polarity reverses. Prominence neutral lines are found in active regions and in the quiet Sun. A number of prominences can be seen in figure 2 in He II. On the disk they are relatively dark and above the limb they are relatively bright. The apparent reason for their darkness on the disk is that they contain cool material with neutral hydrogen and helium with absorbs the emission of extreme-ultraviolet lines. However, this is a matter of current research. Prominences also often erupt from time to time as a component of coronal mass ejections.

Transition region loops and coronal heating

The heating of the transition region and corona is a central, long-standing problem in solar physics. The radiative losses of transition region and coronal plasma occur fast enough that the outer atmosphere of the Sun would collapse in minutes if there was not a constant supply of energy deposited into these plasmas to maintain their high temperatures. The solar transition region is a component of a complex magnetohydrodynamic system. In other words, the temperatures, densities, velocities and magnetic fields of the corona and their evolution are all governed by the equations of magnetohydrodynamics. A complete physical understanding of the solar transition region is only possible if the complete system is understood. The problem of coronal heating encompasses this complete system including the photosphere, chromosphere, transition region and corona (see CORONAL HEATING MECHANISMS). Perhaps the greatest difficulty lies in our inability to measure the Sun's magnetic field above the chromosphere where much of this heating takes place.

The simplest models of the transition region and corona consider the magnetic field as a passive element that constrains plasma flow and heat conduction along the magnetic field lines. The static energy balance models of coronal loops assume that the plasma located along a magnetic field line resembling a coronal loop is uniformly heated along its length by some unspecified mechanism. At the top of the loop where the maximum coronal temperature is reached, the energy input balances the radiative losses and the thermal conduction losses down the field lines to the cooler parts of the atmosphere. In the transition region, the radiative losses are much larger than the local heating rate and are balanced by a dissipation of the thermal conduction flux from the hot corona. These models generally produce an extended corona, resembling the observed CORONAL LOOP structures, and a thin transition that supports the high conductive flux needed. Emission measures of transition region lines, derived from observations, indicate that the volume of the emission measure is small and, in some sense, consistent with a thin transition region.

However there are a number of difficulties with this model. The observed emission measure distribution of the transition region reaches a minimum around 10^5 K with increasing values toward higher and lower temperatures. The static energy balance models are unable to explain the transition region emission measure distribution at temperatures below about 3×10^5 K, in other words, most of the transition region. All of the conductive flux from the corona is radiated away before reaching the middle of the transition region, much less the chromosphere. Further, high-resolution observations of the transition region indicated that it is considerably more extended than predicted by these models. This indicates that it cannot maintain the necessary conductive flux and must itself be locally heated.

Other problems indicate the need for more sophisticated models. For example, the general downflow of transition region plasmas cannot be addressed by the static models but are the basis of steady flow models. These models are capable of reproducing the observed downflows in only the most artificial way and still produce a very thin transition region. The solution to problems of this sort led to models that could include time-dependent flows and heating.

Many of the one-dimensional models continue to predict a very thin transition region. One consequence of this is that hot electrons from the corona are able to penetrate to considerably lower temperatures. In this case, the electron velocity distribution is no longer Maxwellian and greatly complicates the construction of physical models and the spectroscopic diagnostics of these plasmas. The observation that the transition region has a rather shallow temperature gradient indicates that this may not be a real problem but it cannot be totally discounted at this point.

A further discussion of TRANSITION REGION MODELS is presented by V Hansteen.

Very-fine-scale structure and coronal heating

One of the more intriguing properties of the solar transition is the need to invoke the existence of very-fine-scale structures that only sparsely fill the observed transition region structures. In other words, when the transition region is observed at high spatial resolution, it is possible to discern such discrete structures as loops, macrospicules etc. We feel confident that we can measure the volume of such an object. Density-sensitive line ratios are then used to derive electron densities. With the electron density and volume, the emission measure ($\int N_e^2 \, dV$) can be calculated and compared with the emission measure determined simply from line intensities. This comparison generally indicates that the actual volume of emitting material must be much less than what is observed in images of these structures and the actual volume must be only about 1% of the 'observed' volume or less. This can be visualized as the break-up of transition material into thin filamentary strands that follow the magnetic field lines but only fill a fraction of the transition region volume. When a similar analysis is applied to coronal loops, the coronal material seems to completely fill the observed structure. However, the coronal measurements are perhaps not so definitive as in the transition region.

As we will see below, there is evidence for flow patterns in the transition region that are also on very fine spatial scales. These fine-scale structures and flows may be significant in trying to understand how the solar transition region is heated.

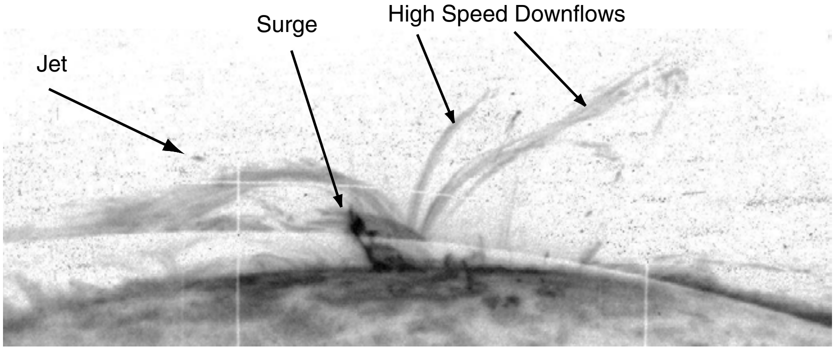


Figure 5. HRTS C IV image of the transition region in an active region at the limb.

Dynamics

As the spectroscopic capabilities of solar ultraviolet instrumentation have improved, it has become clearer that the plasmas at transition region temperatures are highly dynamic. Time sequences of images of transition region structures in the quiet Sun show a continual rearrangement of the network elements and the continual intensity changes in these elements, called 'blinkers'. In the quiet corona, there seems to be a more gradual evolution of the hot structures. Doppler information in transition region spectra also reveals a variety of flows and ejecta, indicating a truly dynamic state.

Flows

Smooth laminar flows of transition region plasmas apparently along magnetic field lines are commonly observed. The speed of sound in solar plasmas varies roughly as the square root of the temperature and has a value of about 40 km s^{-1} at 10^5 K. Flow speeds in the transition are usually subsonic and, in fact, are usually downflows. The typical downflow velocity is about 6 km s^{-1} both in the quiet Sun and in active regions and may approach about 20 km s^{-1}. The net transition region downflow is difficult to understand. There is a net outflow of solar plasma into the solar wind, but the flow velocity associated with this mass loss would be quite small in the transition because of the relatively high densities there. Otherwise we would expect to see a general balance between upflowing and downflowing material but this is not the case.

Persistent supersonic downflows with velocities of 100 km s^{-1} or greater are often seen in and near sunspots, as seen in figure 3. The suspected source for these downflows is the large-scale filamentary transition region structures seen above active regions at the limb. Figure 5 shows filamentary C IV structures above an active region where a surge is in progress.

Further information on TRANSITION REGION FLOWS can be found in the article by P Brekke.

Explosive events

Explosive events have one of the most dramatic signatures in transition region spectra, as seen in figure 6. These

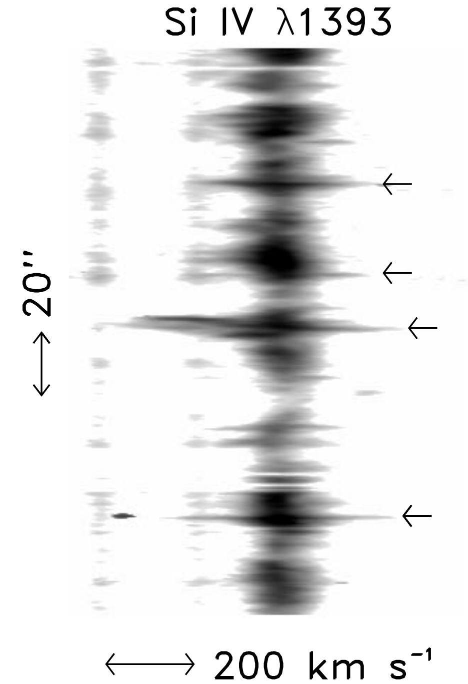


Figure 6. HRTS profiles of Si IV, formed at 7×10^4 K, showing signatures of explosive events in the quiet Sun (arrows).

are most noticeable from their Doppler shifts of about 100 km s^{-1} to the red and/or blue wing of the line in small regions only about 1–2 Mm in extent. Their typical lifetime is about 60 s. The origin of these events can be attributed to magnetic reconnection in a variety of situations. They occur in association with rapidly emerging magnetic flux in active regions, suggesting that the plasma flows are the RECONNECTION jets predicted by the emerging flux flare model. When the positions of explosive events in the quiet Sun are mapped, it is clear that they tend to occur adjacent to magnetic flux elements in the supergranular network boundary. This suggests that explosive events are the result of magnetic reconnection as intranetwork fields are driven by the supergranular flows into the network boundaries. The details of this scenario are now being examined with the SUMER data from SOHO which has been able to directly observe explosive events in conjuction with magnetic flux reconnection.

Further information on EXPLOSIVE EVENTS can be found in the article TRANSITION REGION: EXPLOSIVE EVENTS by D Innes.

Ejections

One of the more puzzling aspects of explosive events is that the accelerated plasma is not observed to travel very far. Nevertheless, there are many examples of transition region plasmas that are ejected outward into the corona. Doppler shifts of small 7 Mm loops that are repeatedly accelerated to 500 km s^{-1} are observed. Doppler blueshifts (outflows) are commonly found at the top of the supergranular network indicating a continual process of plasma ejection taking place there. Macrospicules, with outward velocities as high as 100 km s^{-1}, are a common feature of coronal holes.

In active regions, SURGES are often observed in chromospheric lines such as Hα as well as in the transition region. These are tongues of plasma that are shot out of active region at velocities as high as 100–200 km s^{-1}. Small plasmoids have been observed to traverse large portions of an active region at velocities of 100 km s^{-1}. Figure 5 shows examples of a surge, a jet and prominence material, all in a single observation. Prominences often erupt and form an essential part of a coronal mass ejection. In some cases, the prominence eruption is the first sign of an incipient mass ejection.

Very-fine-scale dynamics

The nonthermal component of spectral line broadening is a signature of random plasma motions with a characteristic velocity of about 20 km s^{-1}. The typical variations in the velocities of the observed larger-scale flows are only on the order of 6 km s^{-1}. Consequently, the fine-scale motions are not simply the continuation of a distribution of velocities over a wide range of spatial scales, as might be expected for a turbulent plasma. The large-scale velocity variations do have the characteristic velocity spectrum of a turbulent Kolmogorov plasma but the fine-scale velocity variations predicted by this spectrum are much less than the observed value of 20 km s^{-1}.

The evidence for fine-scale motions and structures appears to offer a clue for solving the problem of coronal heating. Where this energy comes from and how it is dissipated is a complex problem with no certain solution at this time. For most coronal heating models the source of the energy is the fluid motions of plasmas in the solar convection zone which contort the magnetic fields in a way that amplifies their field strength and creates magnetic topologies that are at a higher energy level than the minimum energy potential field state. As a result, there are currents and mass motions in the outer atmosphere of the Sun that can be dissipated into thermal energy to replace the losses due to radiation. For example, the currents could be dissipated by Joule (resistive) heating and the mass motions through viscous dissipation. The main problem is that the corona is highly conducting and not very viscous. The electrons are quite free to respond to electric fields so that a potential drop is very difficult to maintain. The main source of resistivity is collisions with the heavier ions but this is not very effective. The induced magnetic field from a current sufficient to maintain the corona would result in magnetic loop structures that are extremely twisted, much more so than observed coronal loops which, at most, display only a mild degree of twist.

One way around this problem is to invoke small-scale currents and flows. One suggestion is that coronal heating occurs in many fine-scale magnetic reconnection events called 'nanoflares'. The small-scale motions deduced from transition region line profiles may be evidence for these nanoflares. The nanoflare theory has also been studied with computer simulations which seem to confirm the idea that motions induced by the large-scale photospheric driving motions result in small-scale stochastic energy release events that resemble nanoflares. The small-scale motions and structures in the solar transition region are probably consistent with the nanoflare theory of coronal heating but, as with many of these issues, this is a topic of current research.

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